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Biocolloid and colloid transport through water-saturated columns packed with glass beads: Effect of gravity

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Abstract

The role of gravitational force on biocolloid and colloid transport in water-saturated columns packed with glass beads was investigated. Transport experiments were performed with biocolloids (bacteriophages: ΦX174, MS2) and colloids (clays: kaolinite KGa-1b, montmorillonite STx-1b). The packed columns were placed in various orientations (horizontal, vertical, and diagonal) and a steady flow rate of Q=1.5 mL/min was applied in both up-flow and down-flow modes. All experiments were conducted under electrostatically unfavorable conditions. The experimental data were fitted with a newly developed, analytical, one dimensional, colloid transport model, accounting for gravity effects. The results revealed that flow direction has a significant influence on particle deposition. The rate of particle deposition was shown to be greater for up-flow than for down-flow direction, suggesting that gravity was a significant driving force for biocolloid and colloid deposition.

Mathematical Development

Transport of Dense Colloids:

$$\frac{\partial C(t,x)}{\partial t}+\frac{\rho_b}{\theta}\frac{\partial C^*(t,x)}{\partial t}=D\frac{\partial^2 C(t,x)}{\partial x^2}-U_{tot}\frac{\partial C(t,x)}{\partial x}-\lambda C(t,x)-\lambda^*\frac{\rho_b}{\theta}C^*(t,x)$$

$$U_{tot}=U+U_s \qquad U_s=-f_s\frac{(\rho_p-\rho_w)d_p^2}{18\mu_w}g_{(i)} \qquad g_{(i)}=g_{(-z)}\sin\beta\ \mathbf{i}$$

$$\frac{\rho_b}{\theta}\frac{\partial C^*(t,x)}{\partial t}=k_c C(t,x)-k_r\frac{\rho_b}{\theta}C^*(t,x)-\lambda^*\frac{\rho_b}{\theta}C^*(t,x)$$

Initial & Boundary Conditions:

$$C(0,x)=0$$

$$-D\frac{\partial C(t,0)}{\partial x}+U_{tot}C(t,0)=\begin{cases}U_{tot}C_0 & 0<t\le t_p\\ 0 & t>t_p\end{cases}$$

$$\frac{\partial C(t,\infty)}{\partial x}=0$$

Analytical Solution:

$$C(t,x)=\begin{cases}\Omega(t,x) & 0<t\le t_p\\ \Omega(t,x)-\Omega(t-t_p,x) & t>t_p\end{cases}$$

$$\begin{aligned}\Omega(t,x)=\frac{C_0U_{tot}}{D^{1/2}}\exp\left[\frac{U_{tot}x}{2D}\right]\Bigg\{\int_0^t\int_0^\tau He^{-H\tau}J_0\left[2\left(B\xi(\tau-\xi)\right)^{1/2}\right]\\ \cdot\left\{\frac{1}{(\pi\xi)^{1/2}}\exp\left[\frac{-x^2}{4D\xi}+\left(H-A-\frac{U_{tot}^2}{4D}\right)\xi\right]\right.\\ -\frac{U_{tot}}{2D^{1/2}}\exp\left[\frac{U_{tot}x}{2D}+(H-A)\xi\right]\\ \left.\cdot\operatorname{erfc}\left[\frac{x}{2(D\xi)^{1/2}}+\frac{U_{tot}}{2}\left(\frac{\xi}{D}\right)^{1/2}\right]\right\}d\xi\,d\tau\\ +e^{-Ht}\int_0^t J_0\left[2\left(B\xi(t-\xi)\right)^{1/2}\right]\\ \cdot\left\{\frac{1}{(\pi\xi)^{1/2}}\exp\left[\frac{-x^2}{4D\xi}+\left(H-A-\frac{U_{tot}^2}{4D}\right)\xi\right]\right.\\ -\frac{U_{tot}}{2D^{1/2}}\exp\left[\frac{U_{tot}x}{2D}+(H-A)\xi\right]\\ \left.\cdot\operatorname{erfc}\left[\frac{x}{2(D\xi)^{1/2}}+\frac{U_{tot}}{2}\left(\frac{\xi}{D}\right)^{1/2}\right]\right\}d\xi\Bigg\}.\end{aligned}$$

The various model parameters can be estimated by fitting the above analytical solution to the experimental data with the nonlinear least squares regression package "Colloidfit" (*Sim and Chrysikopoulos,* 1995).

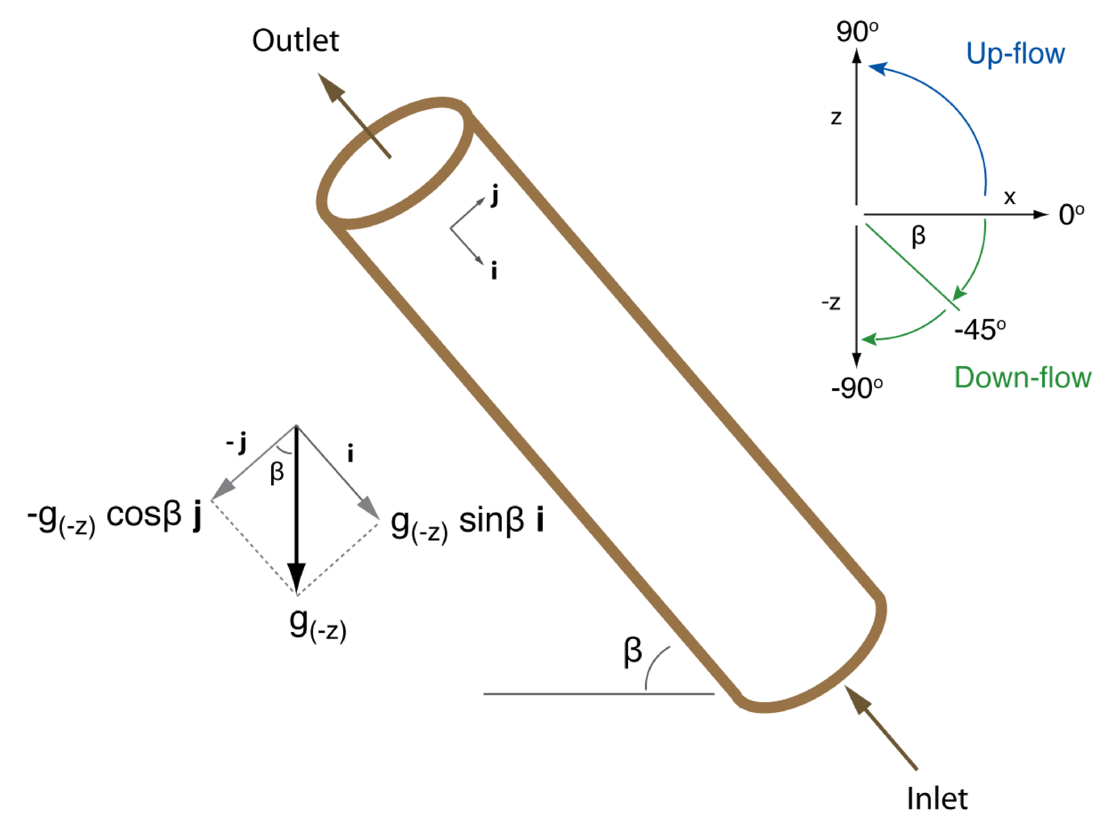

Figure 1. Schematic illustration of a packed column with up-flow velocity having orientation (-i) with respect to gravity. The gravity vector components are: $g_{(i)}= g_{(-z)}\sin\beta\ \mathbf{i}$, and $g_{(-j)}= -g_{(-z)}\cos\beta\ \mathbf{j}$.

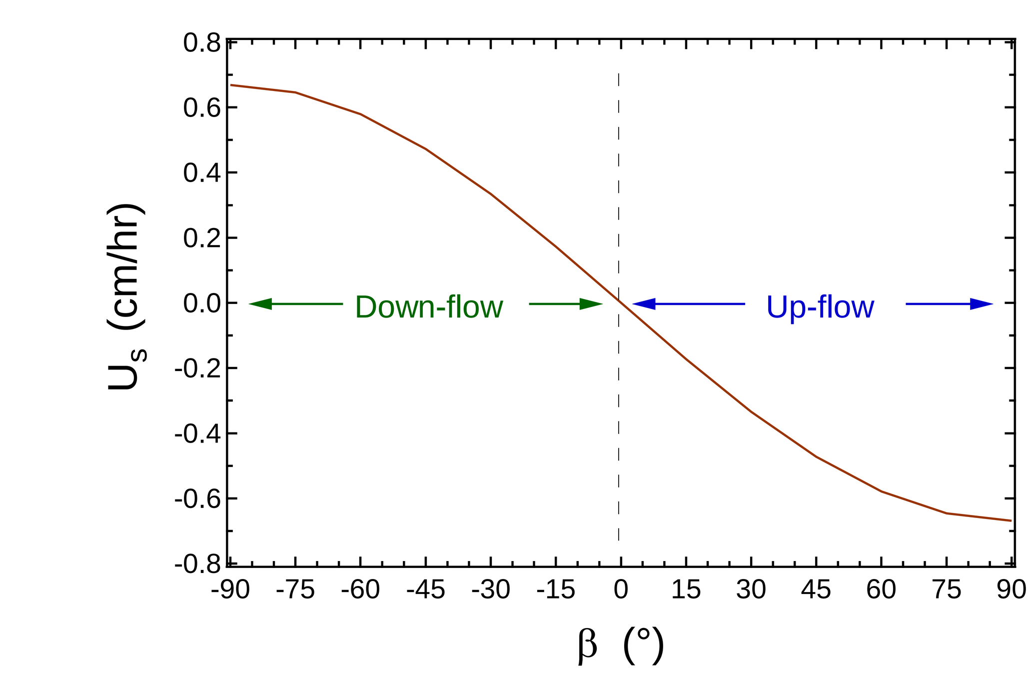

Figure 2. Restricted particle settling velocity as a function of column orientation and flow direction. Here d_p=5 μm, ρ_p=1.15 g/cm³, and f_s=0.9.

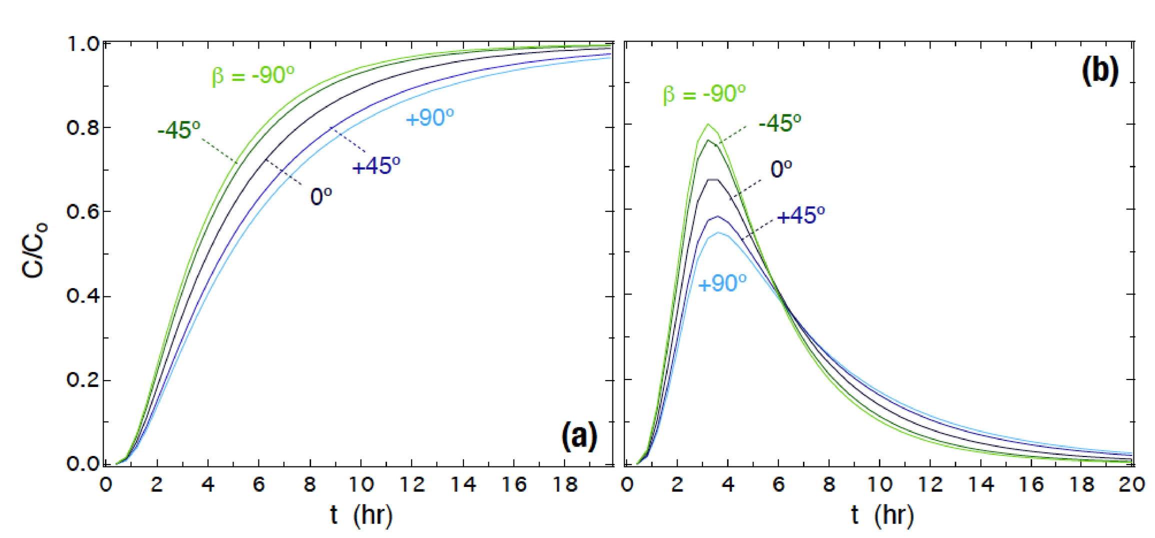

Figure 3. Simulations of normalized colloid break through curves for packed columns with various orientations and flow directions under: (a) continuous, and (b) broad pulse inlet boundary conditions. Here U=4 cm/hr, D=22.5 cm²/hr, θ=0.45, ρ_b=1.63 g/cm³, λ=λ*=0 hr⁻¹, k_c=k_r=0 hr⁻¹, x=15 cm, d_p=5 μm, ρ_p=1.15 g/cm³, and t_p=2 hr.

Experimental Approach

Biocolloids:

MS2: an F-specific single-stranded RNA phage with effective particle diameter ranging from 24 to 26 nm

ΦX174: a somatic single-stranded DNA phage with effective particle diameter ranging from 25 to 27 nm

Colloids:

Kaolinite (KGa-1b): a well-crystallized kaolin from Washington County, Georgia

Montmorillonite (STx-1b): a Ca-rich montmorillonite, white, from Gonzales County, Texas

Column experiments:

- glass columns (2.5 cm diameter and 30 cm length)
- glass beads 2mm in diameter
- constant discharge rate of q=1.5 mL/min,
- 3 pore volumes of biocolloid/colloid suspension in ddH_2O
- 3 pore volumes of ddH_2O solution

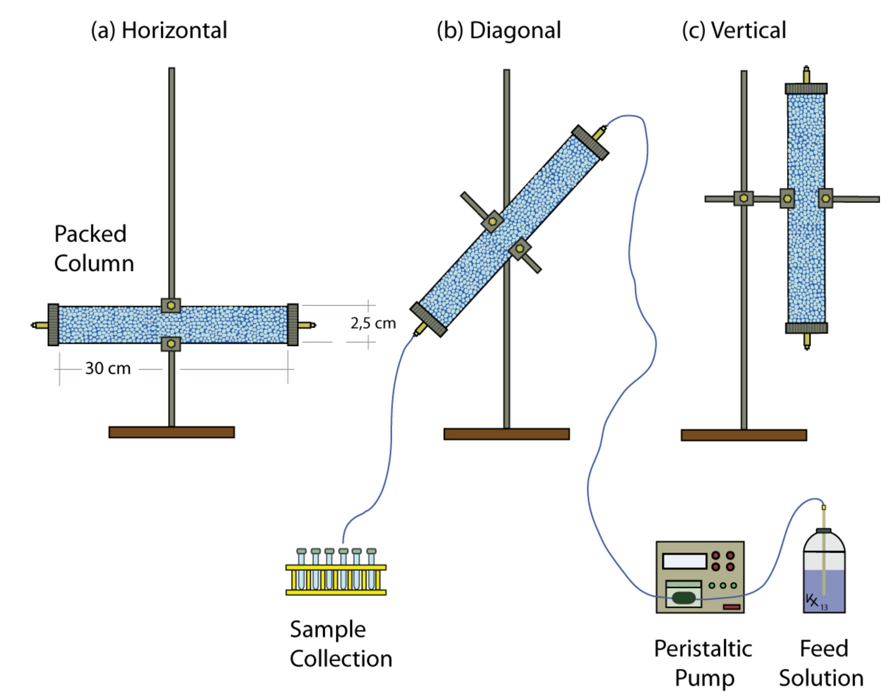

Figure 4. Experimental setup showing the various column arrangements: (a) horizontal, (b) diagonal, and (c) vertical.

Results and Discussion

Table 1. Experimental conditions and estimated mass recoveries

C_o pfu/ml (viruses) mg/L(clays) mol/L(tracer)	Flow Direction[a]	U_{tot} [b] (cm/min)	U_s (cm/min)	D [b] (cm²/min)	k_c [b] (1/min)	M_r (%)	$M_{1(i)}/M_{1(t)}$
ΦX174							
8867	H	0.74264	0.00264	0.95	0.24	100	1.14
5300	VU	0.73971	-0.00029	0.19	0.06	100	0.98
3817	VD	0.74068	0.00068	0.16	0.00	100	0.97
2167	DU	0.73995	-0.00005	0.02	0.35	100	1.01
2833	DD	0.74081	0.00081	0.31	0.28	91.5	1.01
MS2							
1350	H	0.74000	0	0.07	0.18	70.1	1.04
6450	VU	0.73896	-0.00104	0.03	0.05	98.8	1.01
4842	VD	0.74152	0.00152	0.03	0.08	100	1.06
18733	DU	0.73960	-0.0004	0.28	0.22	90.2	1.02
11325	DD	0.74068	0.00068	0.07	0.04	100	1.04
KGa-1b							
62.8	H	0.73741	-0.00259	1.06	0.01	53.5	1.19
50.3	VU	0.73841	-0.00159	0.30	0.02	32.6	1.05
67.6	VD	0.74193	0.00193	0.60	0.00	79.5	1.12
56.6	DU	0.73474	-0.00526	0.68	0.02	37.6	1.07
66	DD	0.74330	0.0033	0.66	0.02	47.9	1.05
STx-1b							
100.1	H	0.73895	-0.00105	0.74	0.01	58.6	1.16
105.9	VU	0.73827	-0.00174	0.55	0.02	65	0.89
102.3	VD	0.74219	0.00219	0.53	0.00	93.8	1
75.9	DU	0.73264	-0.00736	1.18	0.01	61.5	1.31
82.5	DD	0.74439	0.00438	0.52	0.01	83.1	1.06
Tracer							
0.01	H	0.74016	–	0.14		100	
0.01	VU, VD	0.73985	–	0.17		100	
0.01	DU, DD	0.73995	–	0.16		100	

[a] H-horizontal, VU-vertical up-flow, VD-vertical down-flow, DU-diagonal up-flow, DD-diagonal down-flow.
[b] Fitted with ColloidFit.

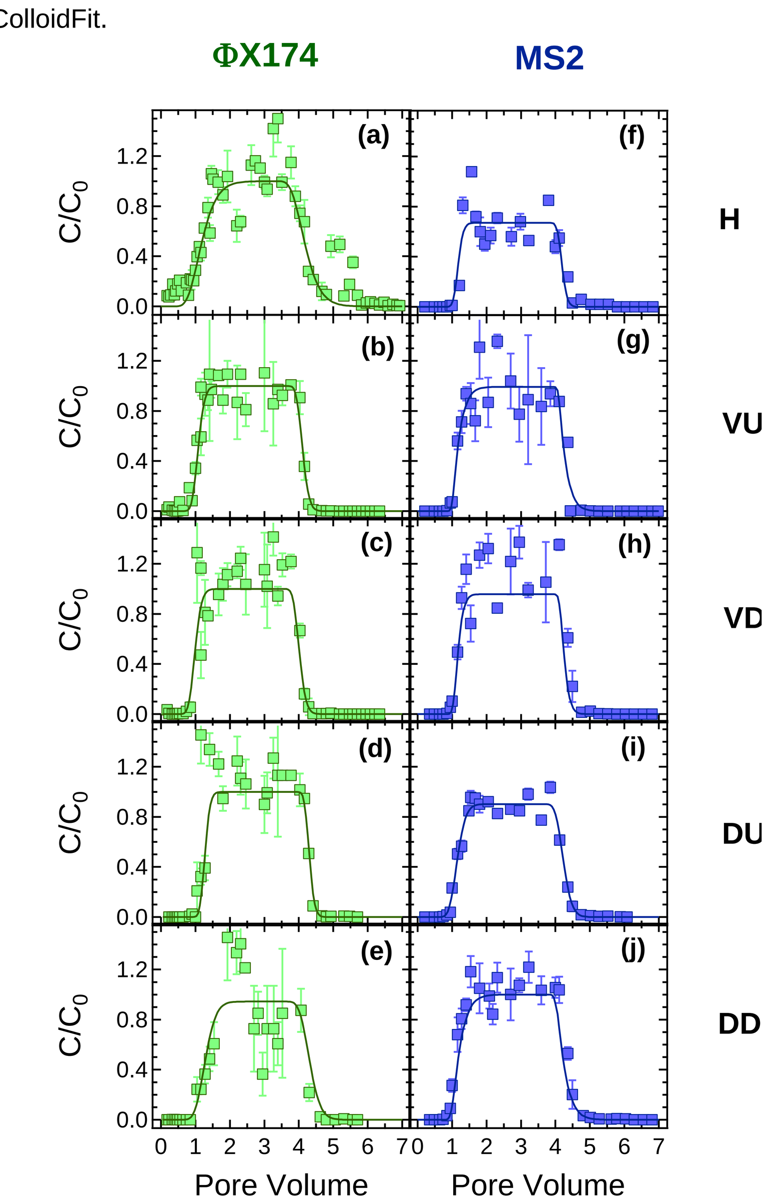

Figure 5. Experimental data (symbols) and fitted model simulations (curves) of (a-e) ΦX174 and (f-j) MS2 breakthrough in columns packed with glass beads with (a,f) horizontal, (b,g) vertical up-flow, (c,h) vertical down-flow, (d,i) diagonal up-flow, and (e,j) diagonal down-flow directional flow conditions. Error bars not shown are smaller than the size of the symbol.

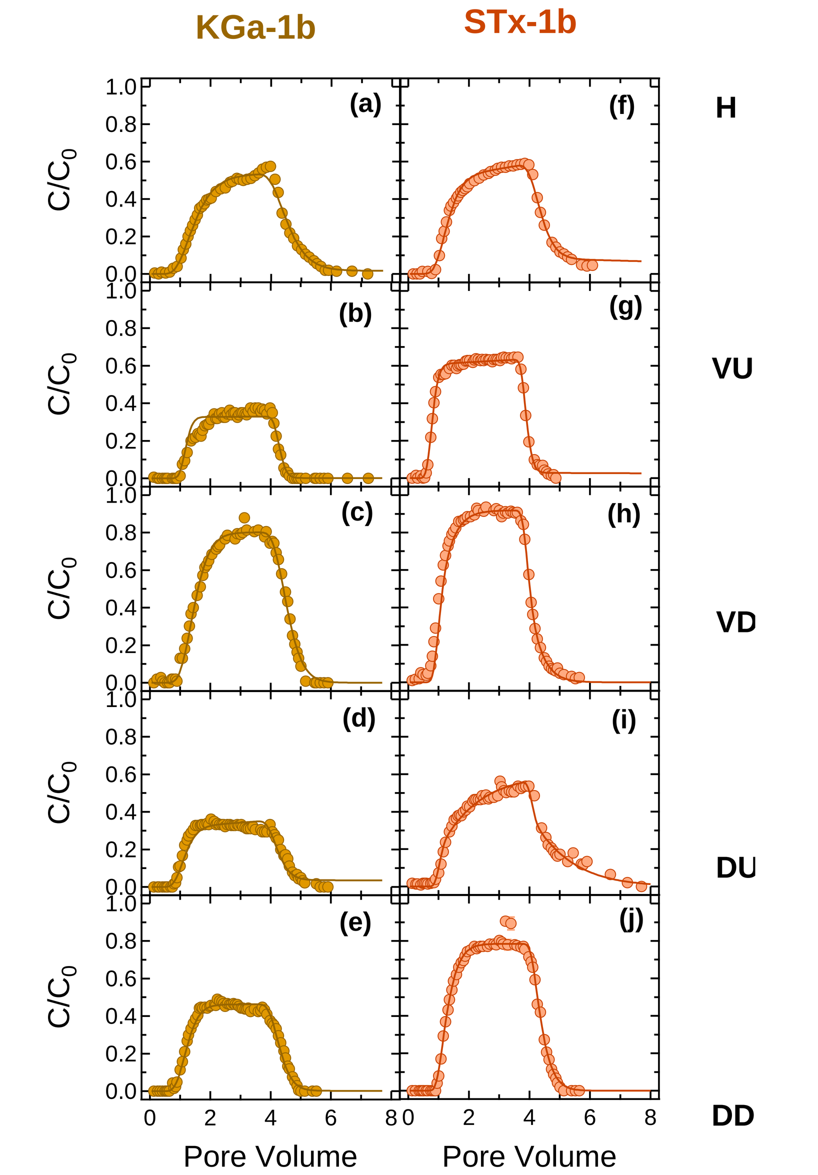

Figure 6. Experimental data (symbols) and fitted model simulations (curves) of (a-e) KGa-1b and (f-j) STx-1b breakthrough in columns packed with glass beads with (a,f) horizontal, (b,g) vertical up-flow, (c,h) vertical down-flow, (d,i) diagonal up-flow, and (e,j) diagonal down-flow directional flow conditions. Error bars are not shown because they are smaller than the size of the symbol.

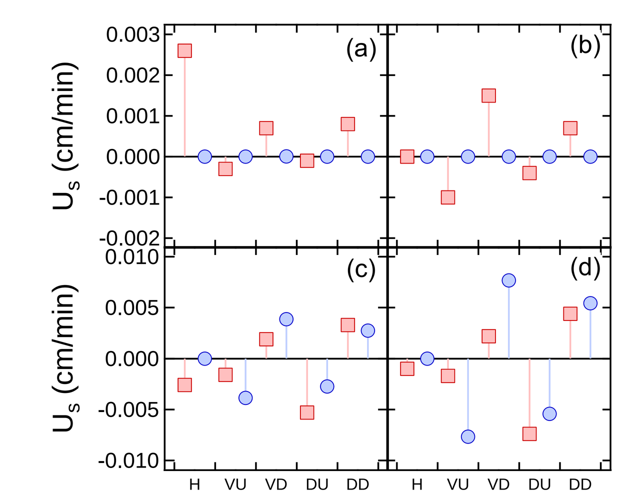

Figure 7. Comparison between theoretically estimated (circles), and fitted (squares) U_s values for: (a) ΦX174, (b) MS2, (c) KGa-1b, and (d) STx-1b. Here, $\rho_{\Phi X174}$=1.6, ρ_{MS2}=1.42, and $\rho_{KGa\text{-}1b}$=$\rho_{STx\text{-}1b}$=2.65 g/cm³. U_s<0 for up-flow and U_s>0 for down-flow experiments.

From Table 1 it is evident that U_s=0 for horizontal flow, U_s>0 for down-flow, and U_s<0 for up-flow. Note that the absolute U_s values for the clays were much higher than those for the bacteriophages owing to their lager size and density.

Clearly, there is much better agreement for the denser clay particles (ρ_p=2.65 g/cm³) than for the biocolloids, which are only 40-60% denser that water and lead to relatively smaller restricted settling velocities. Based on the fitted k_c values listed in Table 1, particle attachment is generally higher for up-flow than down-flow experiments.

This observation is in agreement with the results reported by *Basha and Culligan* (2010). In contrast, *Ma et al*. (2011) found that colloidal deposition rate constants, under conditions favorable to deposition, were slightly higher for down-flow than up-flow experiments.

The fitted D values (see Table 1) are smaller for the smaller (bacteriophage) than the larger (clay) particles, suggesting that the dispersivity is increasing with particle size. Note that this result is exactly opposite than previously reported findings (*Keller et al.*, 2004; *Vasiliadou and Chrysikopoulos*, 2011; *Syngouna and Chrysikopoulos*, 2011).

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